“Understanding the Hydrodynamics of Batoid Ray Propulsion”

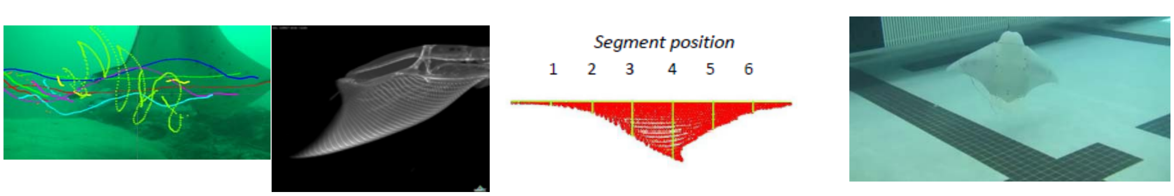
Background: This project seeks to enhance our understanding of the underlying physics of batoid ray locomotion. These animals were chosen because of their high-efficiency cruising ability, agile maneuverability, ability to follow bottom terrain, ability to hold station, quietness, and high speed.

Project Objective: The objective of this project is to develop the scientific foundation necessary to understand and create the next generation bio-inspired underwater vehicle. Understanding the underlying physics of batoid swimming—through quantification of the three-dimensional geometry, anatomy and swimming motions and the analysis of gait, frequency, and material properties—enables us to fully explore the efficiency and economy design space as a function of velocity. Physical and virtual models of various rays have been built to mimic the kinematic displacements derived from the actual rays. These models are used in both experimental and numerical hydrodynamic studies to quantify ray locomotion performance. Dynamic modeling for ray swimming is being developed and tested to find optimality. Neural control strategies are being used to monitor and control actuators to ensure efficient and robust locomotion.

Status: The project is in its 5^{th} and final year. Accomplishments include quantification of biological musculoskeletal structure and swimming kinematics; quantification of the role of skeletal structure on performance via integration of a biomechanics model with a fluids model; defined hydrodynamic wake resonance as an underlying principle of efficient unsteady propulsion; ability to determine thrust and efficiency of various actuation strategies without direct measurement through simple scaling analysis; development of active tensegrity structures to produce batoid-like kinematic displacements; development of central pattern generator (CPG)-controlled actuated tensegrity structures with feedback for robust and efficient locomotion; design and fabrication of free swimming robotic batoids to test hypotheses on unsteady hydrodynamic propulsion.

A study of flexible propulsors—the foundation for ray swimming—has provided key insights into the basis for this type of locomotion. The study has found that (i) flexibility can be utilized to substantially increase both thrust production and propulsive efficiency in comparison to a rigid pitching panel; (ii) while there is an enhancement in the thrust response when operating at resonance, the maximum thrust produced by the flexible panels occurs at a frequency 1.5 times that of the resonant frequency; (iii) there exists an optimal flexibility to maximize efficiency, being either too stiff or too flexible causes a degradation in propulsive efficiency; (iv) depending on panel flexibility, optima in efficiency are found below, at, and above the resonant frequency of the panels; and (v) the thrust production, power consumption, and propulsive efficiency follow a simple scaling law derived by considering the non-dimensional terms in the governing equations.

This project is developing robotic batoid rays for the purpose of scientific investigations as described above. As such, although these robots have limited performance capabilities commensurate with scientific studies, this research is expected to lead in the future to more efficient propulsion for underwater vehicles.



(1) Time-resolved motions of batoid ray; (2) CT scan of batoid ray; (3) numerical model of ray; (4) physical model of ray undergoing testing in pool

ONR POC: R. Brizzolara, Ph.D. Principal Investigator: Professor Hilary Bart-Smith, University of Virginia

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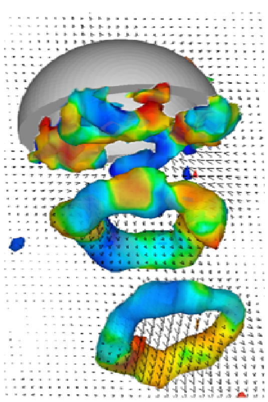
“Understanding the Hydrodynamics of Jellyfish Propulsion”

Background: This project seeks to enhance our understanding of the underlying physics of how jellyfish achieve relatively low energy locomotion and create thrust production with relatively very little body mass. Jellyfish provide a unique opportunity to understand and develop methods of efficient propulsion since they exhibit a relatively low cost of transport (energy required to propel a given mass over a given distance) and their transparent/translucent bodies allows fluid to be imaged around all its surfaces, facilitating wake dynamics studies. Furthermore, jellyfish observed in nature range from few centimeters in diameter to few meters in diameter, providing opportunity to understand the changes in modes of propulsion with respect to size.

Project Objective: Investigate fundamental science underlying the propulsion of jellyfish. The approach includes investigations into actual jellyfish as well as investigations using physical models. The advantage of physical models is that certain characteristics and parameters (such as the size, flexible margin and segments of the bell) can be changed, and this allows systematic investigation of the effects of these parameters on propulsion. Research questions being addressed are: what are the coherent vortex structures relevant for propulsion and the moving surface kinematics affecting their production; are there any important vortex interactions affecting stability of these vortices; can we establish unifying principles of animal propulsion that control thrust and maneuverability and acceleration from the flow physics for a flexible surface, and how does the animal actively manage streamwise and spanwise camber to optimize propulsion?

Status: The project is in its 5th and final year. The project has advanced our understanding of how jellyfish use their body’s elasticity to enhance thrust, for example, how the jellyfish’s body generates vorticity in the water and the effect of vortex – vortex interaction on efficiency, and the effects of a flexible margin. For example, passive energy recapture (the production of thrust between strokes) and flexible bell margins both increase energy efficiency and provide insights to the observed low cost of transport. During the course of the project, several model jellyfish have been built for the purpose of scientific investigations of these and other phenomena. Fluid flow measurements as well as computer simulations are key tools in this research.



Volumetric 3-component velocimetry allows observation and quantification of fluid put in motion by jellyfish and how this is affected by the kinematics and morphometrics of the jellyfish bell.

Although the robotic jellyfish developed in this project have modest performance capabilities (appropriate for scientific studies), this research is expected to lead in the future to more efficient propulsion for underwater vehicles.

ONR POC: R. Brizzolara, Ph.D.

Principal Investigator: Professor Shashank Priya, Virginia Tech

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